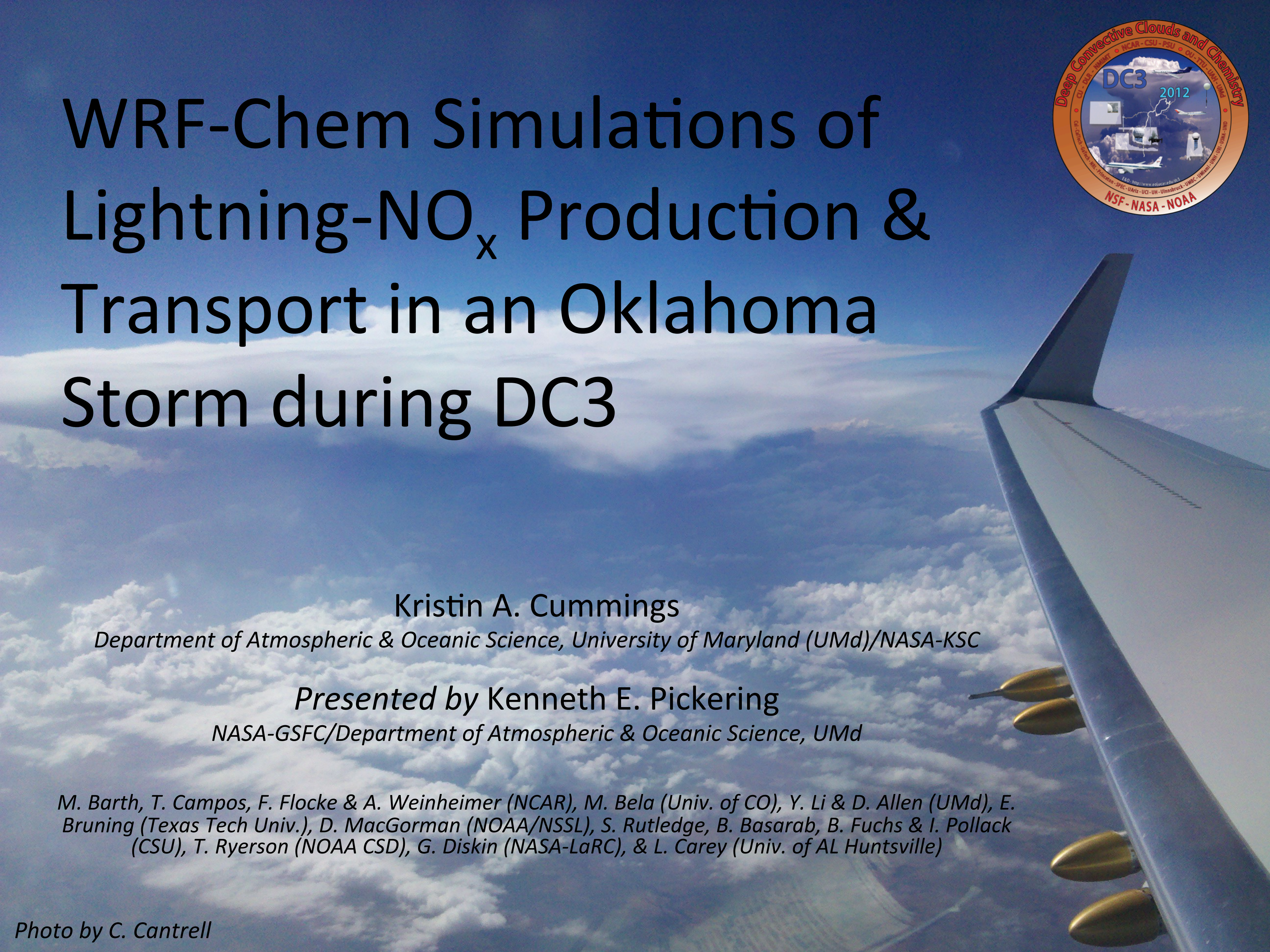


WRF-Chem Simulations of Lightning-NO_x Production & Transport in an Oklahoma Storm during DC3

Kristin A. Cummings
Department of Atmospheric & Oceanic Science, University of Maryland (UMd)/NASA-KSC

Presented by Kenneth E. Pickering
NASA-GSFC/Department of Atmospheric & Oceanic Science, UMd

M. Barth, T. Campos, F. Flocke & A. Weinheimer (NCAR), M. Bela (Univ. of CO), Y. Li & D. Allen (UMd), E. Bruning (Texas Tech Univ.), D. MacGorman (NOAA/NSSL), S. Rutledge, B. Basarab, B. Fuchs & I. Pollack (CSU), T. Ryerson (NOAA CSD), G. Diskin (NASA-LaRC), & L. Carey (Univ. of AL Huntsville)

Photo by C. Cantrell

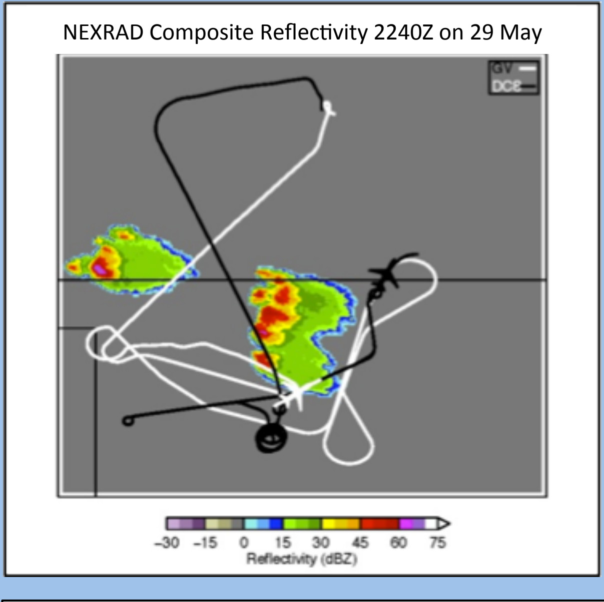
Key Objectives

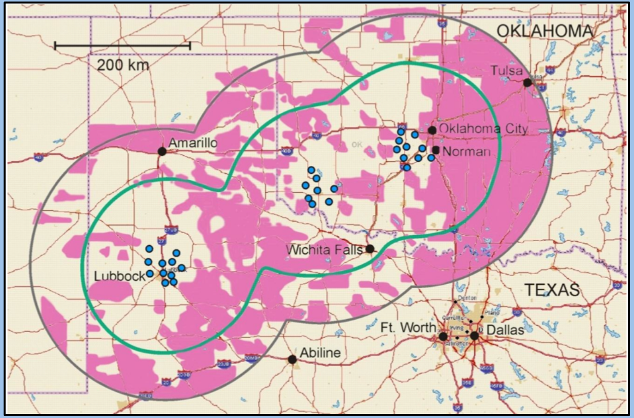
- Continuation of previous work, which:
  - Compared flashes generated by flash rate parameterization schemes (FRPSs) in a WRF-Chem model simulation with lightning observations:
    - Oklahoma Lightning Mapping Array (OK LMA)
    - National Lightning Detection Network (NLDN)
  - Tentatively concluded lightning-generated NO_x (LNO_x) production is around 125 moles $flash^{-1}$

- Current work objectives:
  - Define and incorporate new lightning flash channel vertical distributions and IC:CG ratios into the WRF-Chem model based on lightning data from a LMA for the storm of interest
  - Analyze distribution of observed and model-simulated trace gas species in storm inflow and outflow
  - Determine NO production scenario for IC and CG lightning

Background

- Severe convection developed ~21Z May 29 along KS/OK border and continued until 04Z May 30
- Aircraft sampled storm and its environment from 20Z May 29 to 01Z May 30
  - DC-8 focused on storm inflow & outflow
  - GV & Falcon concentrated on outflow
- Ground-based data included:
  - Dual-Doppler radar (NEXRAD level II regional)
  - Shared Mobile Atmospheric Research and Teaching Radar (SMART-Radar)
  - NLDN cloud-to-ground flash data
  - OK LMA flash initiation density data


NEXRAD Composite Reflectivity 2240Z on 29 May



Blue circles: LMA stations
Green outline: Extent of 3-D lightning mapping capability
Gray outline: Extent of 2-D lightning detection

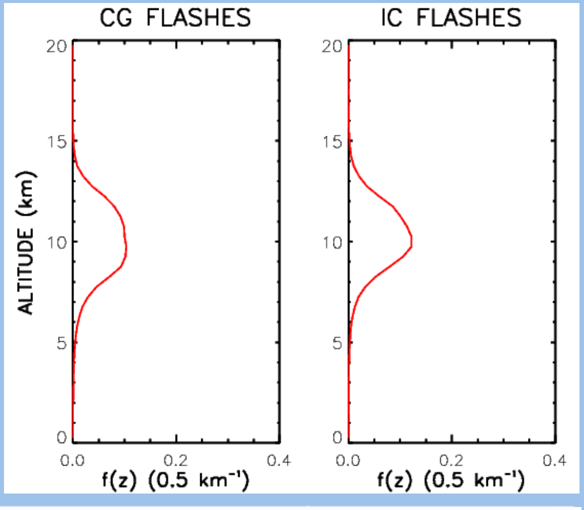
WRF-Chem Model V3.6.1

- Grid resolution: dx = dy = 1-km, dz = 50-250 m
- Initialized with 18Z NAM ANL (6-hr) for boundary conditions
- Lightning Data Assimilation from 18-21Z (*Fierro et al., 2012*)

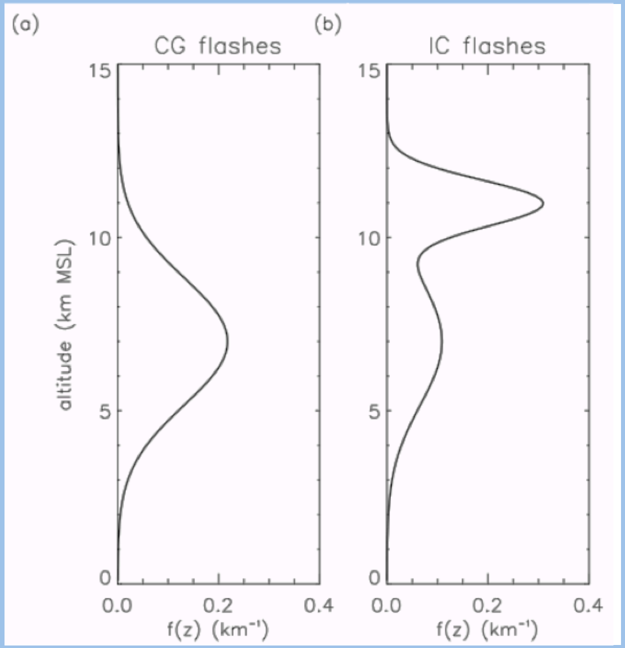
Type of Scheme	Selection for Simulation
Microphysics	Morrison
Planetary boundary layer	Yonsei University (YSU)
Land surface	Noah
Radiation (short & longwave)	Rapid radiative transfer model for GCMs (RRTMG)
Photolysis	F-TUV
Trace gas chemistry	MOZART
Flash rate	➢ Updraft volume based on AL supercells (UP510_S) ➢ Coarsely prescribed IC:CG ratios (*Boccippio et al., 2001*) replaced with IC:CG ratios based on LMA and NLDN obs
LNO$_x$	Flash segment vertical distribution based on observations

LNO$_x$ Parameterization Scheme

- Replaced the typical lightning flash channel distributions (*DeCaria et al., 2000; 2005*) with observed IC & CG vertical distributions
  - Used flash channel segment data from observed storm's respective LMA network
  - IC & CG distributions for 29 May both appear to be single Gaussian where channels maximize at ~10km (-42°C)
  - Previous distributions were set to maximize the lightning channels at -15°C (IC & CG) and -45°C (IC), or 6km and 10.5km, respectively
- Found 125 moles flash^{-1} provided best fit with observed anvil NO$_x$ when using *DeCaria et al.* vertical distributions. This scenario:
  - Is much smaller than mean value of 500 moles flash^{-1} found in previous mid-latitude simulations (*Ott et al., 2010*)
  - Will be tested using new distributions
- Horizontal placement of NO based on reflectivity ≥ 20 dBZ in each grid cell



New IC & CG distributions for 29 May case



DeCaria et al. (2000, 2005)

Methodology

FRPS	Reference
Max vertical velocity (*Wmax*)	Price & Rind (1992)
Cloud top height (*CTH*)	Price & Rind (1992)
Updraft volume (*UpVol*)	Deierling & Petersen (2008)
Ice water path (*IWP*)	Petersen et al. (2005)
Precipitation ice mass (*PIM*)	Deierling et al. (2008)
Ice mass flux product (*IMFP*)	Deierling et al. (2008)
Graupel volume (*CSU_GEV*)	Basarab et al. (2015)
35-dBZ volume (*CSU_VOL35*)	Basarab et al. (2015)
Precipitation ice mass (*CSU_PIM*)	Basarab et al. (2015)
Graupel echo volume (-40°<T<-5°C; *ALGEV5*)	Carey et al. (2015)
ALGEV5 for supercells (*ALGEV5_S*)	L. Carey
Graupel echo volume (-40°<T<-10°C; *ALGEV10*)	Carey et al. (2015)
ALGEV10 for supercells (*ALGEV10_S*)	L. Carey
Updraft volume(w>5m s^{-1}, -40°C<T<-10°C; *ALUP510*)	Carey et al. (2015)
ALUP510 for supercells (*ALUP510_S*)	L. Carey

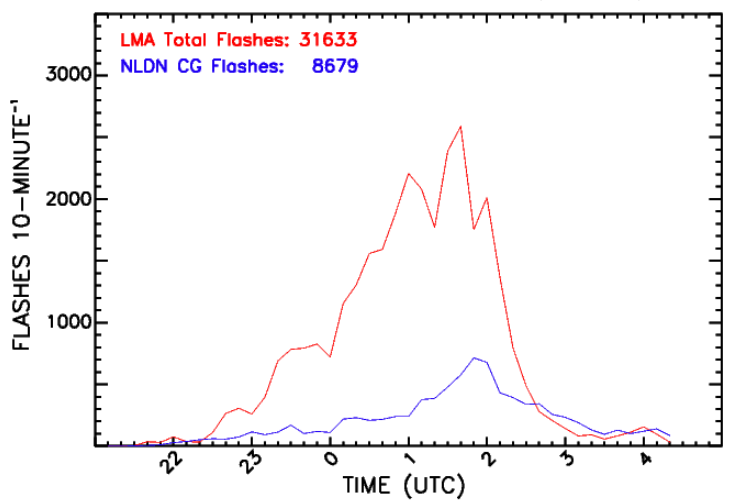
- Compared flash rate trends over the observed and model-simulated storm's lifetime
    - Used 15 different FRPS, including those from literature, as well as recently developed schemes from DC3 radar and LMA data
    - Selected the FRPS that reasonably represented the total observed flashes over the storm and the flash rate trends from the LMA
- Assumed LNO_x production is 125 moles $flash^{-1}$ and will adjust as necessary
- Analyzed trace gas species (i.e., CO, NO_x, O_3) using model-simulated values and aircraft (DC-8 & GV) observations to:
    - Create probability distribution function (PDF) plots in storm outflow
    - Evaluate convective transport
    - Determine best fit NO production scenario

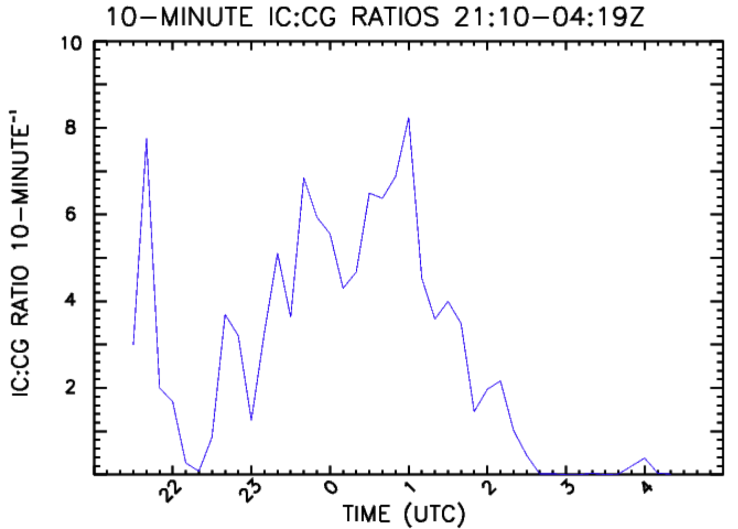
IC:CG Ratios

- Coarsely prescribed IC:CG ratios from *Boccippio et al. (2001)* provide a mean IC:CG of 3.90 ± 0.49 over the region where the severe convection occurred

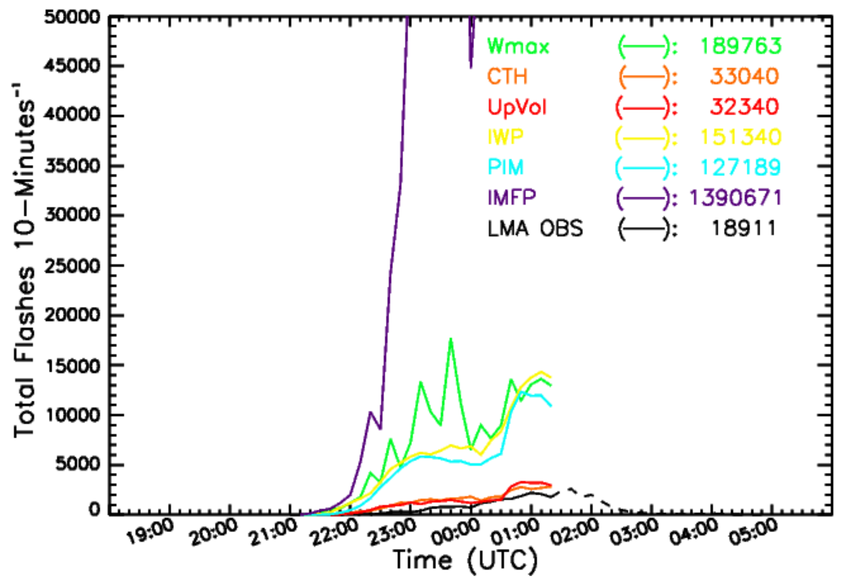
- LMA total and NLDN CG flashes indicate the IC:CG ratio fluctuates over the lifetime of the convection on 29 May
  - Mean IC:CG ratio over storm lifetime is 2.73 ± 2.51

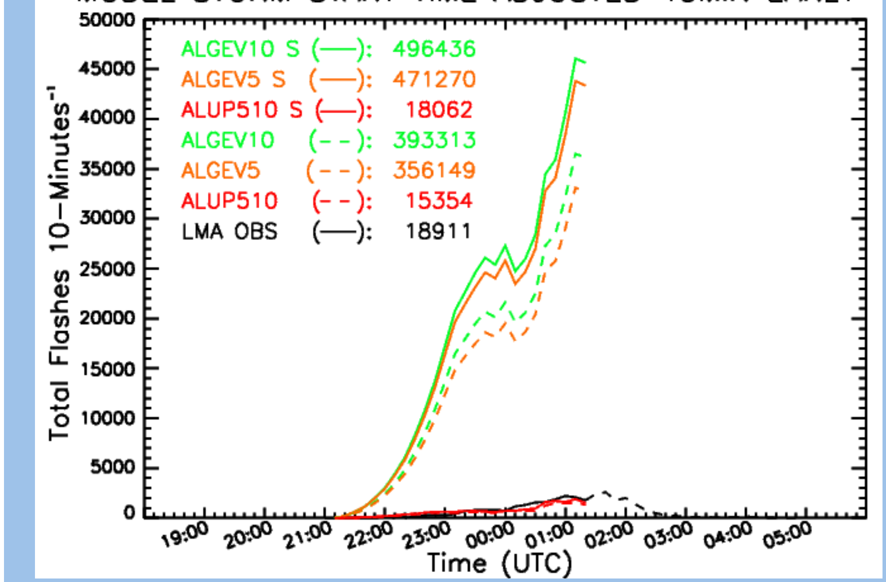
- Time evolving IC:CG ratios are applied in the model to the storm of interest, while climatological IC:CG values are used in the area surrounding the storm

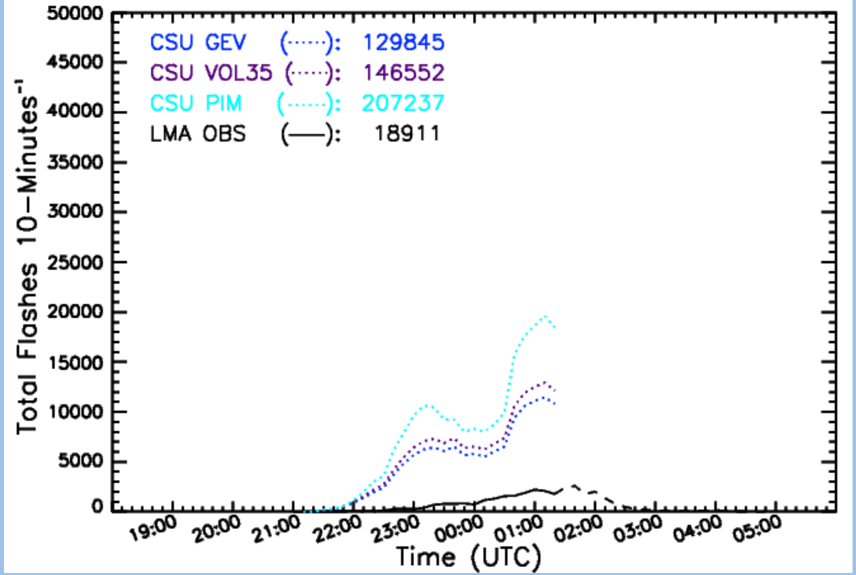




Model Flash Rates vs. Observations



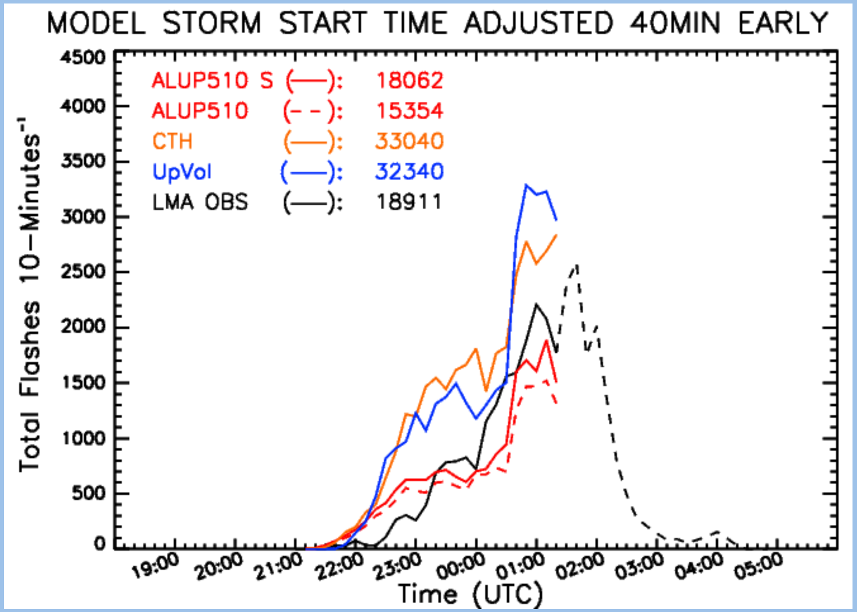




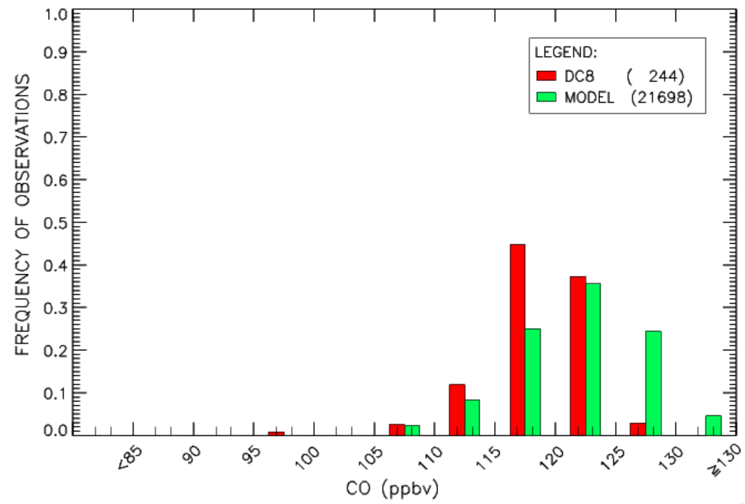
- Observed storm occurs 21:10-04:10 UTC
- Model-simulated storm onset is delayed 40 min (21:50 UTC)
- Plotted observed & model-simulated flash rates to both begin at 21:10 UTC

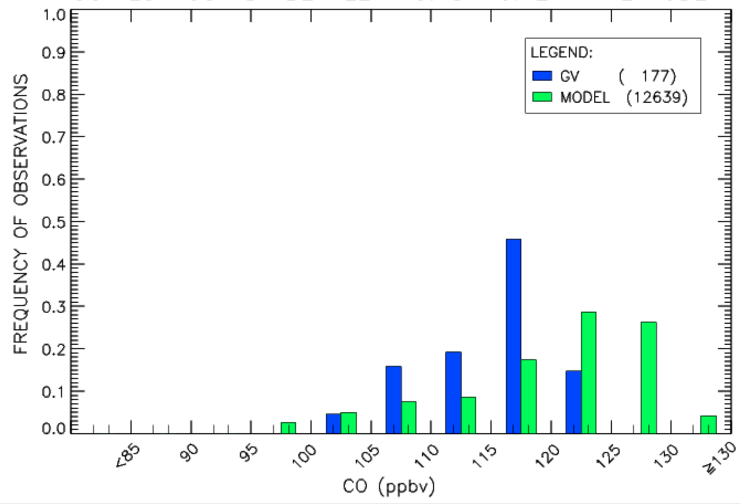
Model Flash Rates vs. Observations

- Selected the updraft volume FRPS for Alabama supercells (ALUP510_S) for use in model
  - Based on updraft (w > 5 m s^{-1}) volume and mixed-phase region (-40°C < T < -10°C)
- All FRPSs incorporating hydrometeors overestimate (*by 7-74x*) the total flash observations
- All FRPSs developed for the Colorado region overestimate (*by 7-11x*) the total flash observations
  - 35-dBZ volume was generally developed from storms with shallow warm cloud depths (< 1km), while the 29 May case has a deep warm cloud depth (2.5km)



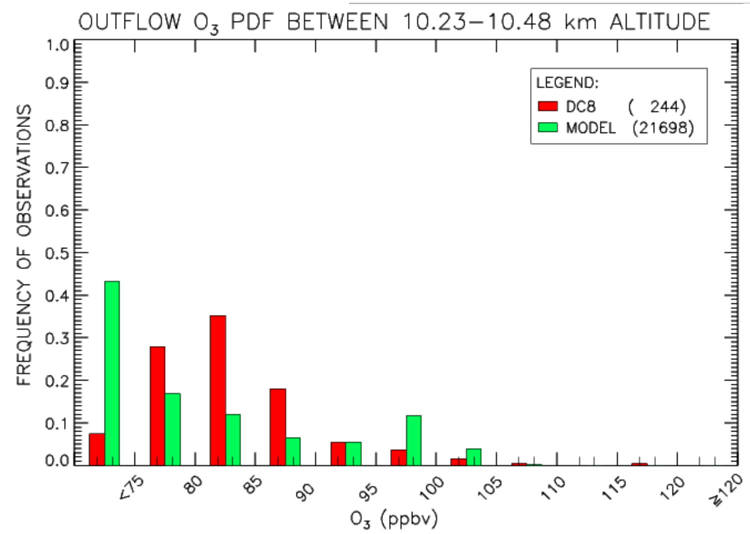
CO & O_3 PDFs in Storm Outflow

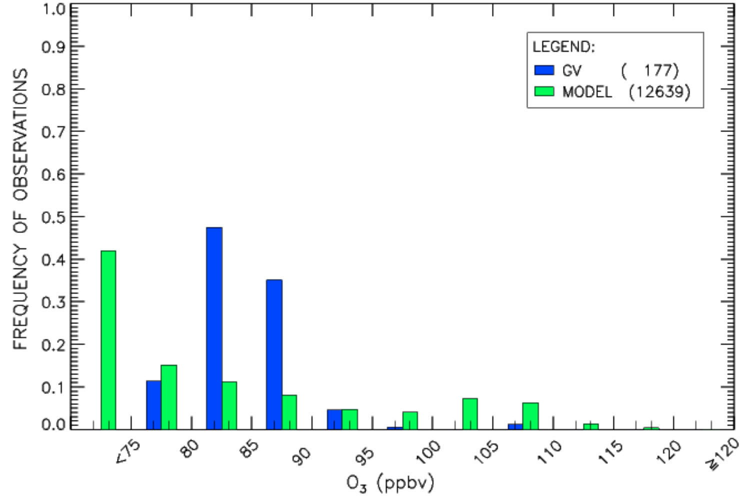

OUTFLOW CO PDF BETWEEN 10.23–10.48 km ALTITUDE


OUTFLOW CO PDF BETWEEN 10.48–10.72 km ALTITUDE

Model-simulated CO peaks at <u>larger</u> values than observations

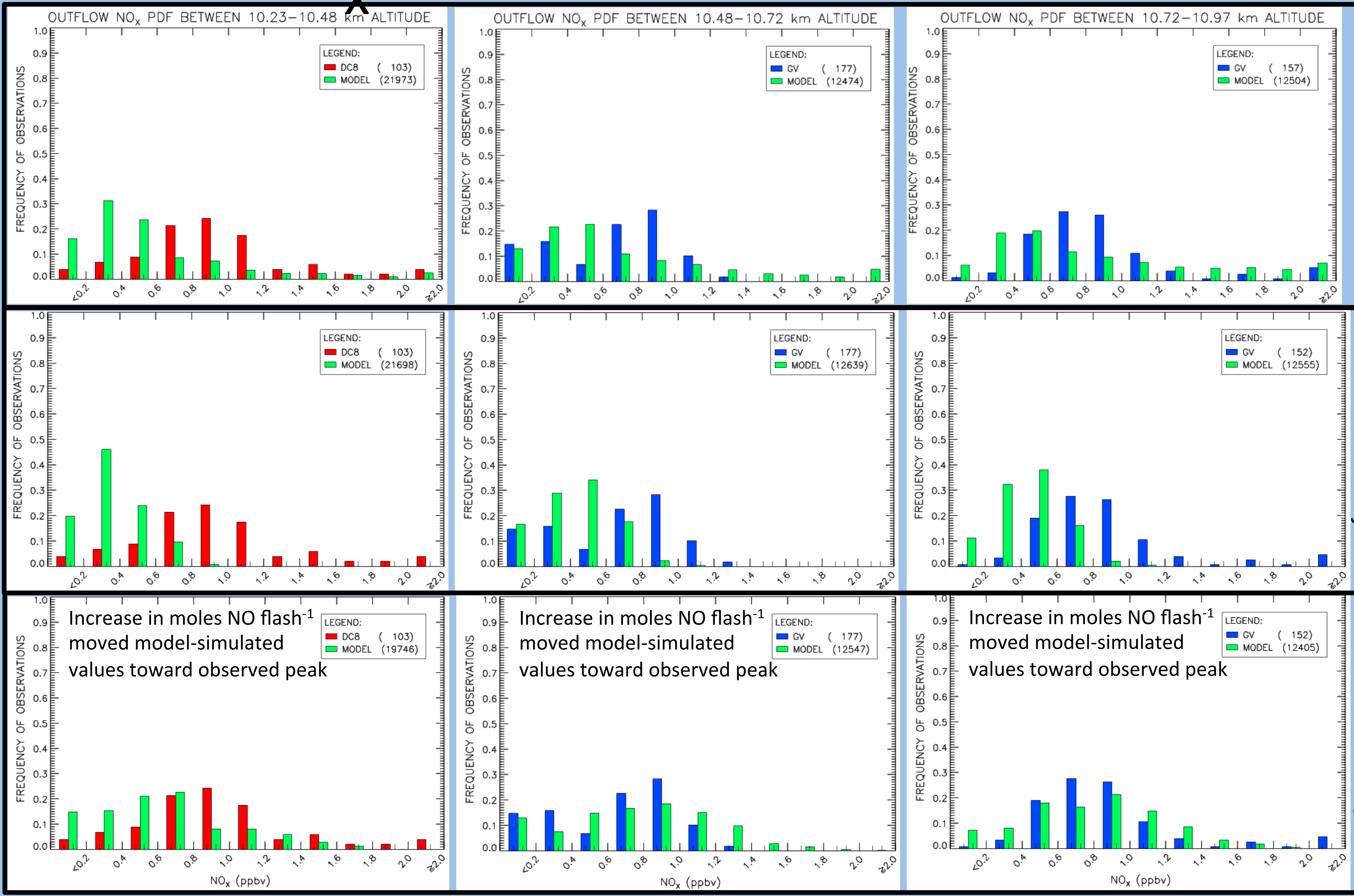
Model-simulated O_3 peaks at <u>smaller</u> values than observations


OUTFLOW O_3 PDF BETWEEN 10.23–10.48 km ALTITUDE


OUTFLOW O_3 PDF BETWEEN 10.48–10.72 km ALTITUDE

* Comparison of peak vertical velocities (*not shown*) suggests model-simulated values may be 20% greater than the SMART-Radar observations

NO_x PDFs in Storm Outflow



Increase in moles NO flash^{-1} moved model-simulated values toward observed peak

Increase in moles NO flash^{-1} moved model-simulated values toward observed peak

Increase in moles NO flash^{-1} moved model-simulated values toward observed peak

DeCaria et al. (2000, 2005) with 125 moles NO flash^{-1}

***New lightning channel vert. distrib.** for 29 May 2012 with 125 moles NO flash^{-1}*

*New lightning channel vert. distrib. for 29 May 2012 with **250 moles NO flash^{-1}***

Conclusions

- A single model domain at fine resolution (1-km) produces a storm of roughly the same size and with similar characteristics as the observed

- FRPSs based on hydrometeors or Colorado storms are not ideal for the severe Oklahoma convection observed on 29 May
  - Selected a FRPS based on **updraft volume ($w > 5$ m s^{-1}) within the mixed-phase region of Northern Alabama supercells**

- LNO_x production may be closer to **250 moles flash^{-1}**
  - Removed influence of an IC upper lightning channel on NO_x by replacing the IC & CG vertical distributions (*DeCaria et al. 2000, 2005*) with observed lightning channel distributions from 29 May
  - May be less than the mean value for mid-latitude storms (*500 moles flash^{-1}*) due to presence of smaller flashes

Future Work

- 29-30 May 2012 Oklahoma severe convection:
  - Finalize NO production scenario for IC and CG LNO_x scheme
  - Test other NO production scenarios from the literature and compare against the scenario selected for 29 May
    - 500 moles flash^{-1} (*Ott et al., 2010*)
    - Lightning Nitrogen Oxides Model (LNOM) results for IC & CG flashes (*Koshak, 2014*)
  - Investigate O_3 changes within the cloud and downwind of the storm
- 6-7 June 2012 Colorado squall line:
  - Test and select one of the 15 FRPSs in the WRF model
  - Determine NO production scenario for IC and CG LNO_x scheme
  - Investigate O_3 changes within the cloud and downwind of the storm
- Compare the results between the storms to:
  - Investigate which FRPSs are most appropriate for the two types of convection
  - Examine the variation in LNO_x production
- Compare simulated LNO_x results from WRF-Chem with other previously studied mid-latitude thunderstorms

Acknowledgements

- Regional NEXRAD level II data provided by Cameron Homeyer (NCAR)
- NLDN data collected by Vaisala, Inc. and archived by NASA MSFC

QUESTIONS?

Photo by C. Cantrell

References

Basarab, B. M., S. A. Rutledge, and B. R. Fuchs (2015), An improved lightning flash rate parameterization developed from Colorado DC3 thunderstorm data for use in cloud-resolving chemical transport models, J. Geophys. Res., 120, 9481-9499, doi: 10.1002/2015JD023470.

Boccippio, D. J., K. L. Cummins, H. J. Christian, and S. J. Goodman (2001), Combined satellite- and surface-based estimation of the intracloud-cloud-to-ground lightning ratio over the continental United States, Mon. Wea. Rev., 129, 108-122.

Carey, L. D., E. V. Schultz, C. J. Schultz, A. L. Bain, R. M. Mecikalski, W. Deierling, W. A. Petersen, and K. E. Pickering (2015), Kinematic and microphysical control of lightning flash rate over Northern Alabama, 95th American Meteorological Society Annual Meeting, Phoenix, AZ, 4-8 January 2015, 9.1.

DeCaria, A. J., K. E. Pickering, G. L. Stenchikov, J. R. Scala, J. L. Stith, J. E. Dye, B. A. Ridley, and P. Laroche (2000), A cloud-scale model study of lightning-generated NO_x in an individual thunderstorm during STERAO-A, J. Geophys. Res., 105, doi: 10.1029/2000JD900033.

DeCaria, A. J., K. E. Pickering, G. L. Stenchikov, and L. E. Ott (2005), Lightning-generated NO_x and its impact on tropospheric ozone production: A 3-D modeling study of a STERAO-A thunderstorm, J. Geophys. Res., 110, D14303, doi:10.1029/2004JD05556.

Deierling, W., and W. A. Petersen, (2008), Total lightning activity as an indicator of updraft characteristics, J. Geophys. Res., 113, D16210, doi:10.1029/2007JD009598.

Deierling, W., W. A. Petersen, J. Latham, S. Ellis, and H. J. Christian (2008), The relationship between lightning activity and ice fluxes in thunderstorms, J. Geophys. Res., 113, D15210, doi:10.1029/2007JD009700.

Fierro, A. O., E. R. Mansell, C. L. Ziegler, and D. R. MacGorman (2012), Application of a Lightning Data Assimilation technique in the WRF-ARW model at cloud-resolving scales for the tornado outbreak of 24 May 2011, Mon. Wea. Rev., 140, 2609-2627, doi:10.1175/MWR-D-11-00299.1.

Koshak, W. (2014), Global Lightning Nitrogen Oxides Production, in: *The Lightning Flash, 2nd Edition*, Eds. V. Cooray. 819-860, The Institution of Engineering and Technology, Stevenage, Herts, England.

Petersen, W. A., H. J. Christian, and S. A. Rutledge (2005), TRMM observations of the global relationship between ice water content and lightning, Geophys. Res. Lett., 32, L14819, doi:10.1029/2005GL023236.

Price, C., and D. Rind (1992), A simple lightning parameterization for calculating global lightning distributions, J. Geophys. Res., 97, 9919-9933, doi:10.1029/92JD00719.